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SO₂ ON VENUS: A FINAL CROSS-CALIBRATION WITH PIONEER VENUS

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This is the first semi-annual progress report for NASA Grant NAG5-1913 (SwRI Project No. 15-4914), SO₂ on Venus: A Final Cross-Calibration with Pioneer Venus.

In our previous report, we noted that we had successfully completed all of IUE observations which were proposed. A total of 7 Venus spectra were obtained. In the present reporting period, essentially all of the associated data reduction and analysis activities were completed, and Drs. Stern, Barker, and Na met to collaborate on data interpretation.

The model atmosphere used in this analysis is similar to the one used in the analysis of the Pioneer Venus observations (Esposito, et al. 1979, 1988) and the previous IUE observations (Na, et al. 1990). In this model, sulfuric acid aerosols with a radius of about 1 micron are mixed uniformly with Rayleigh scattering gases throughout the cloud layer. There are two wavelength-independent absorbers. First, the aerosols are assumed to have a single scattering albedo of 0.98, and second a pure absorbing layer with an optical depth of 0.2 is added at an altitude of 75 mbar. The variable parameters in this model are the mixing ratios of SO₂ at the cloud top (40 mbar level), and the scale height of SO₂ at the same altitude. Model spectra were calculated using a radiative transfer code utilizing a Markov chain method. Each model calculation takes into account the multiple scattering and the vertical inhomogeneity of the atmosphere.

We reported those initial results at the 1992 meeting of the AAS Division of Planetary Sciences (Barker, Stern, and Na 1992; see attached). The important finding we have reached is that the 1991 IUE observations indicate that the long-term decline in Venus SO₂ abundance has either halted or reversed. Our simultaneous groundbased measurements made on the McDonald Observatory 2.7m corroborate this result. We are now preparing a paper describing these IUE results for publication in *Icarus*. With the IUE results reduced, we are also beginning a project to compare the 1991 IUE results to Pioneer Venus UV spectra made on the same dates.

References

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- Esposito, L.W., J.R. Winick, A.I.F. Stewart, 1979. Sulfur Dioxide in the Venus Atmosphere: Distribution and Implications. *GRL*, **6**, 601.
- Esposito, L.W., et al. 1988. Sulfur Dioxide at the Venus Cloud Tops, 1978-1986. *JGR*, **93**, 5267.
- Na, C.Y., L.W. Esposito, and T.E. Skinner, IUE Observations of Venus SO₂ and SO. *JGR*, **95**, 7485.

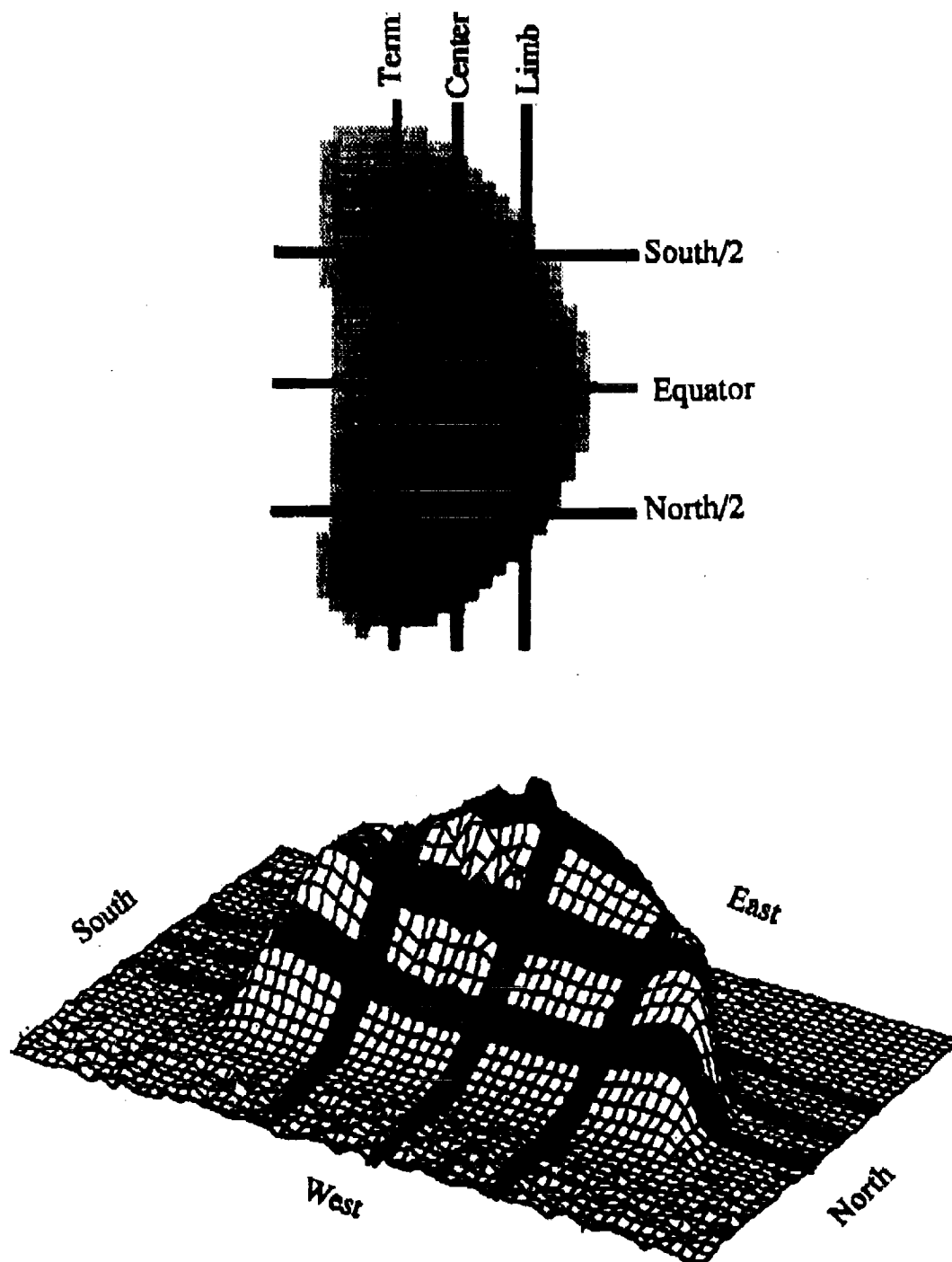
OBSERVATIONS

When Venus was at elongation in early November 1991 we obtained ground-based, spatially resolved spectra and images of Venus with Large Cassegrain Spectrograph and a TI 800x800 CCD detector on the 2.7 m telescope at McDonald Observatory. Spectra and images were obtained on November 1, 2, and 3, but only those obtained on November 2nd are presented here. The spectral coverage was from the effective atmospheric cutoff at 3050Å to 3700Å at an effective resolution of about 3Å. The images were taken in two interference filters, one in the SO₂ absorption at 3150(±100)Å and one in the continuum at 3430(±30)Å. The spectra and images were taken within a few minutes of each other and under excellent seeing conditions (~1 arcsecond). The exposures were less than 1 second for both the images and spectra which effectively canceled any image motion. Spectral observations of a solar analog were obtained at similar airmasses to the Venus spectra.

On the same days in November 1991, we obtained IUE spectra with the LWP camera and spectrograph. Seven IUE images were obtained as part of a long term effort to monitor the SO₂ abundance with IUE. IUE observations span 1979 to 1991 with future observations scheduled in early 1993. We report on two IUE spectra in this paper. A 1 minute exposure (LWP 21613) on November 2nd and a 3 minute exposure (LWP 21622) on November 3rd.

The six slit positions (1 arcsec) for the ground-based data are illustrated in Fig. 1. Also shown in Figure 1 is the IUE 3 arcsecond, circular aperture. The ground-based guiding errors were 1 arcsecond or less. Whereas, the IUE drifted considerably during the exposures resulting in at least 5 arcsec smearing of the 3 arcsecond aperture for the shorter exposures on the disk of Venus. The longer exposures had proportionally greater smearing. Consequently, the IUE spectra

Figure 1: Slit Positions on the Disk of Venus (single aperture is IUE)



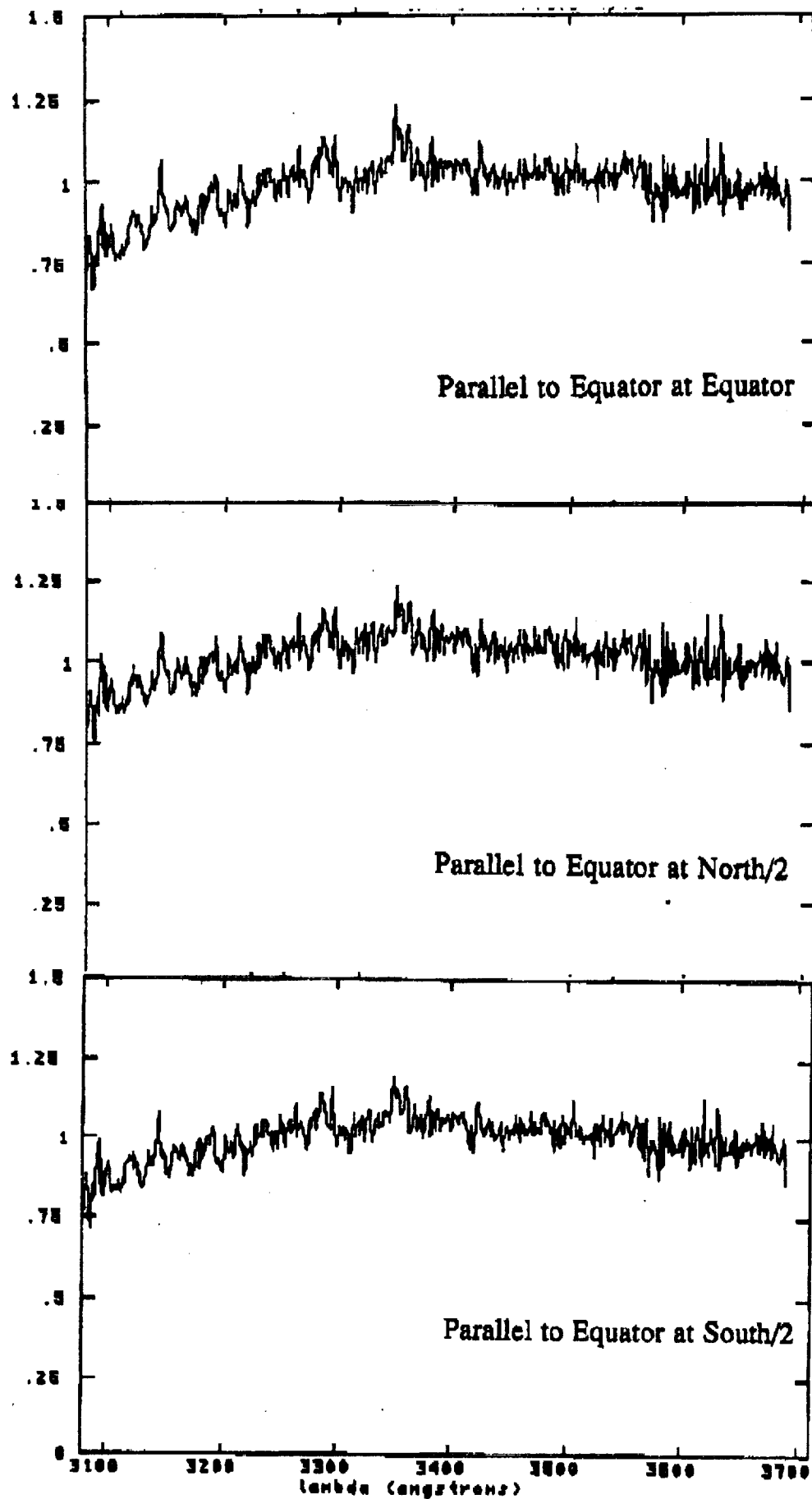


Figure 2a-c: Venus reflectance spectra at the slit positions shown in Fig. 1

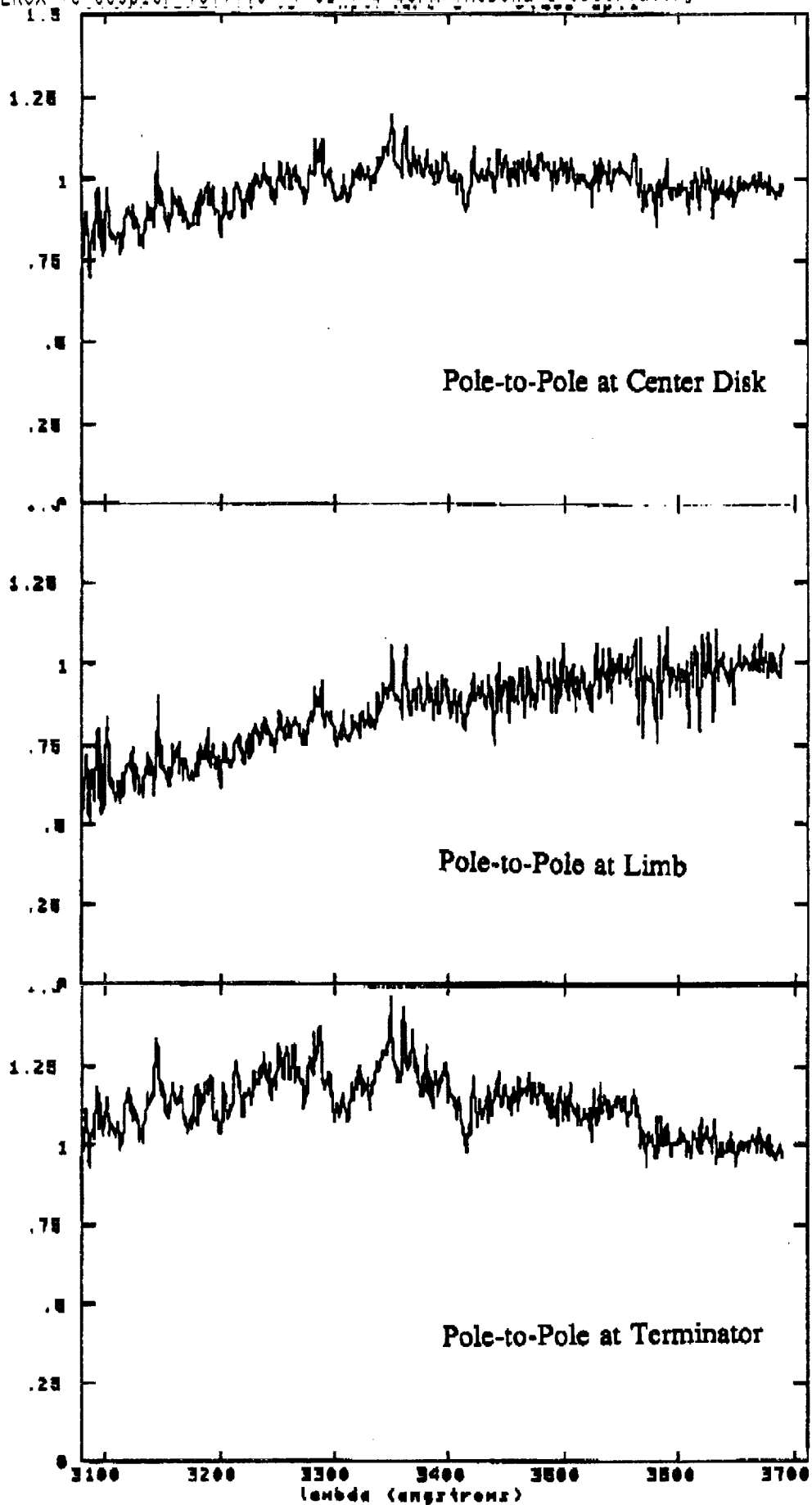


Figure 2d-g: Venus reflectance spectra at the slit positions shown in Fig. 1

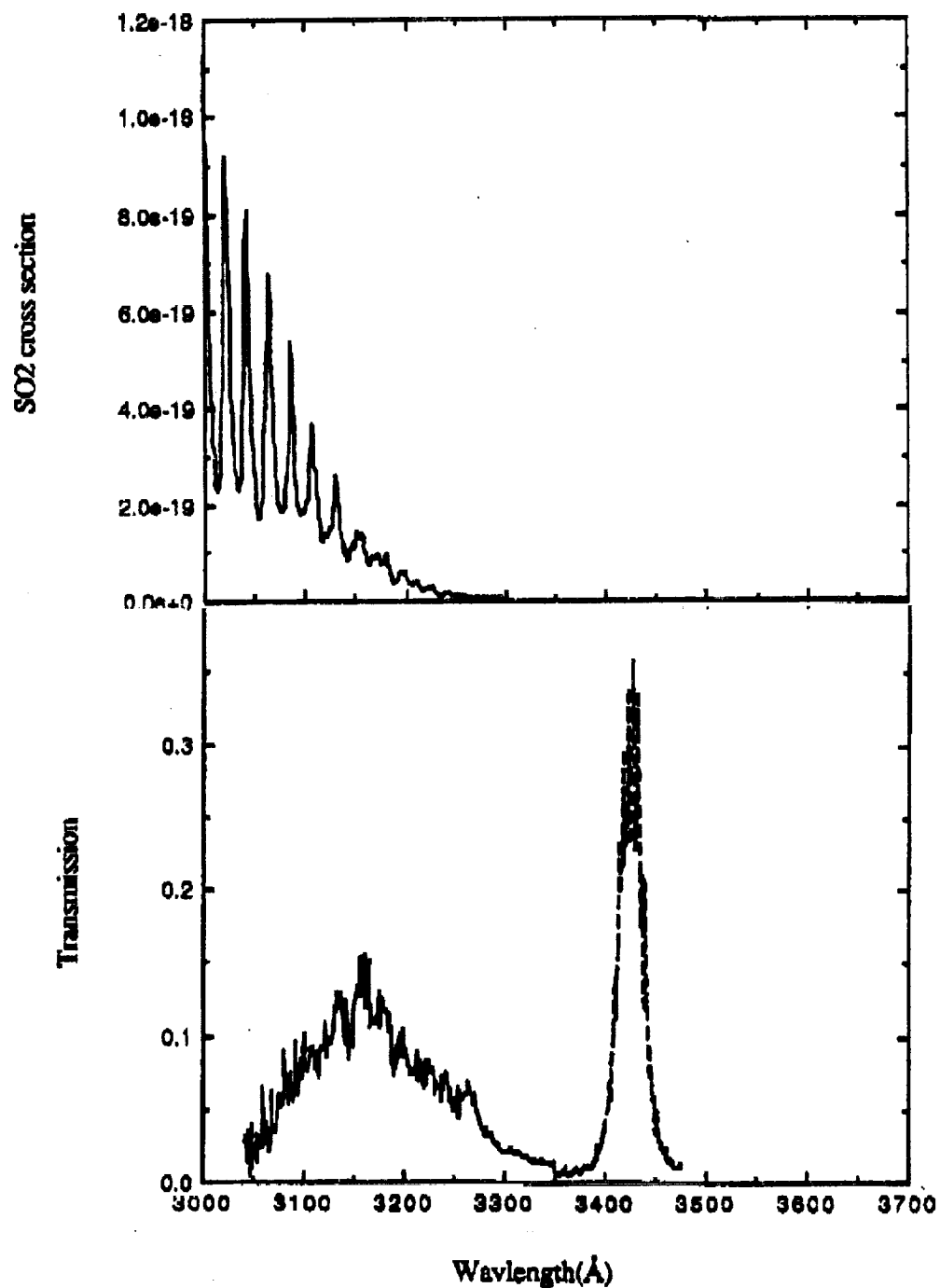


Figure 3: Transmission curves for the interference filters and the SO₂ cross section between 3050 and 3700 Å.

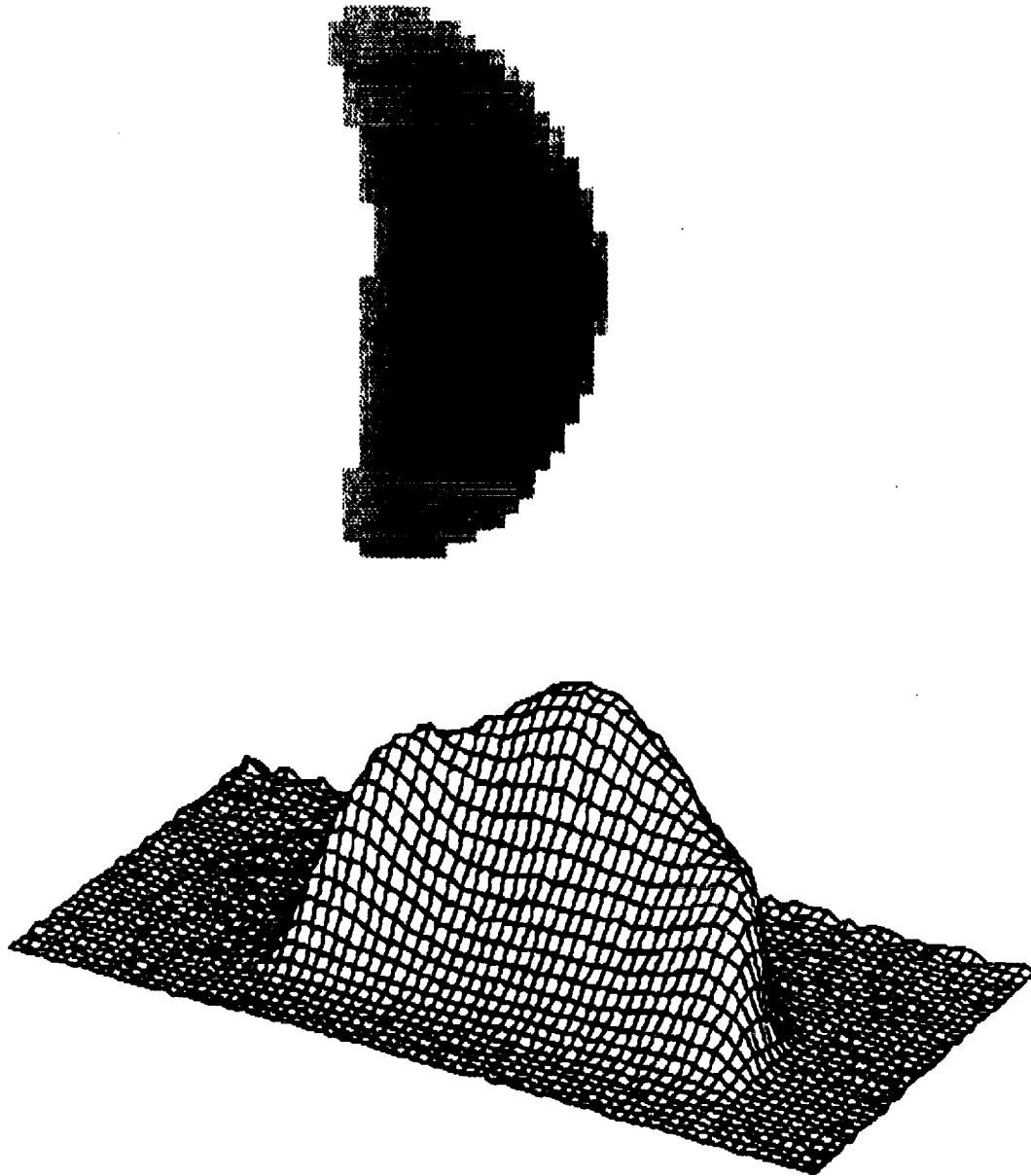


Figure 4b: Grayscale and surface intensity image at 3427Å.

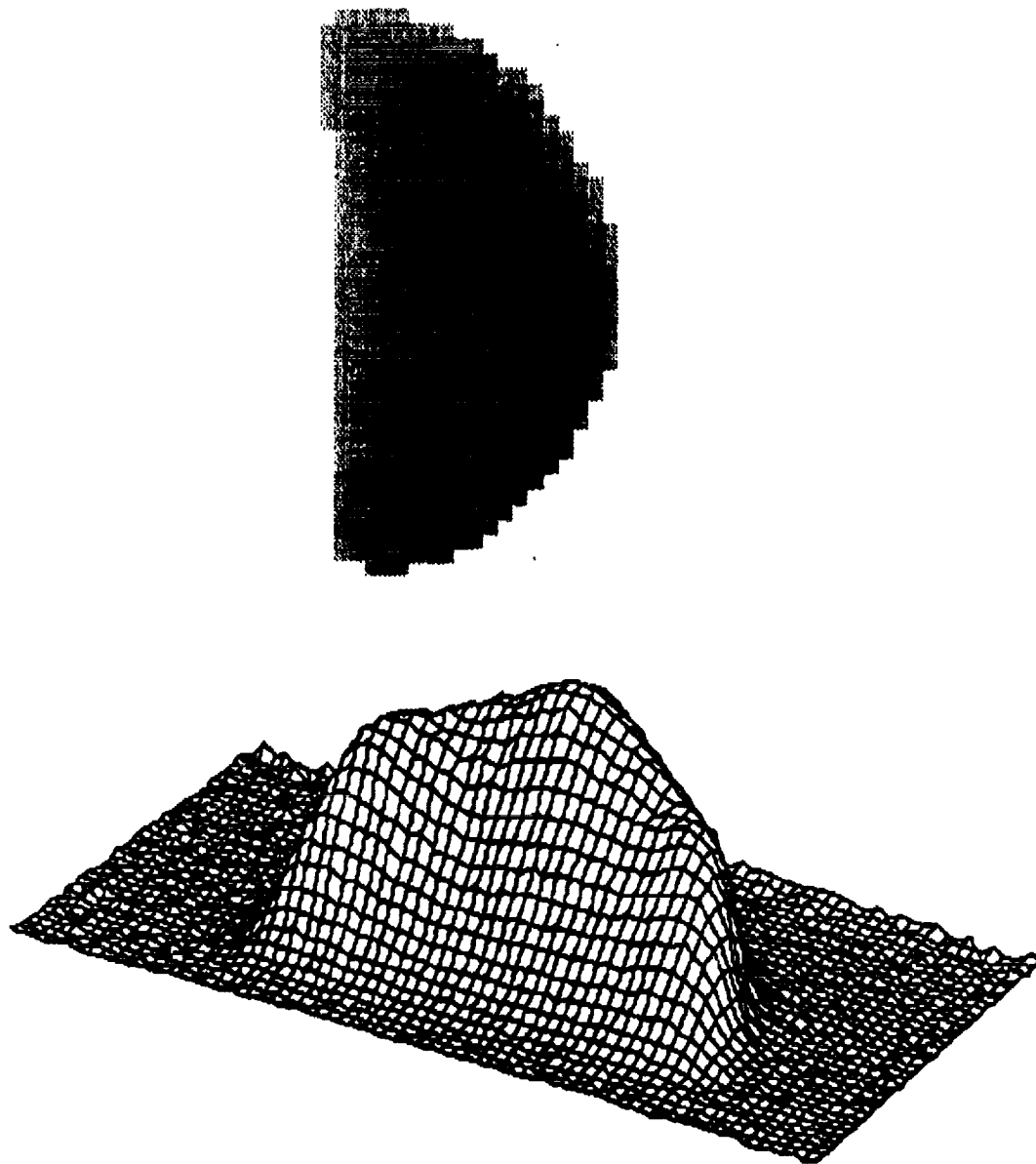


Figure 4a: Grayscale and surface intensity image at 3150Å.

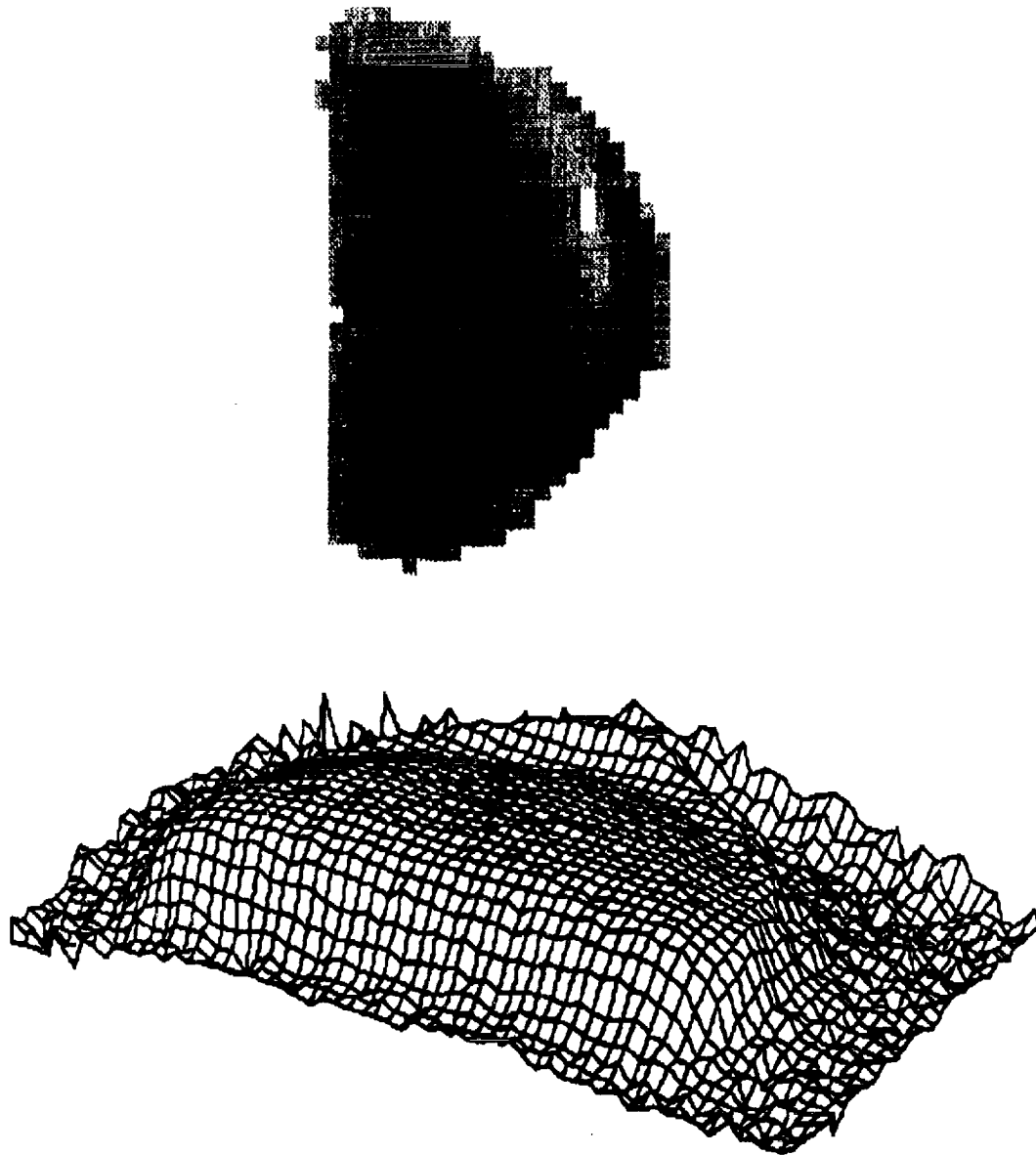


Figure 4c: Grayscale and surface intensity of ratio image ($3150\text{\AA}/3427\text{\AA}$)

DATA REDUCTION

The CCD spectra were reduced to ratio spectra using standard IRAF reduction packages. The Venus spectra and the solar analog spectrum were corrected for the difference in airmass using standard extinction coefficients. Then the solar analog spectrum was cross-correlated with each Venus spectrum to produce a shifted solar spectrum to match the solar spectrum reflected by Venus. This shifting technique produced smoother ratio spectra resulting in the relative reflectance spectra shown in Figs. 2a-g. All the Venus reflectance spectra are quite similar in shape, except for the terminator and limb spectra. When these two spectra are averaged, the result is almost identical to the rest. The difference between the terminator and limb spectra will not be addressed in this presentation. All of the spectra in Figs. 2a-g were averaged to produce a disk average spectrum (Fig 5) for comparison to the IUE spectra which effectively sampled the entire disk due to the larger aperture and guiding errors.

The IUE spectra were reduced to fluxes with standard IUE packages. The short wavelength data are presented in I/F reflectance units. Long wavelength spectra have had the reflected solar spectrum removed by dividing by a SUSIM (Van Hoosier, et.al.1988, *Astrophys. J. Let* 27,163) solar spectrum smoothed to IUE resolution. The IUE spectra for November 2nd and 3rd are presented in Figs 6 and 7.

The transmission curves for the two interference filters are presented in Fig. 3 along with the SO₂ cross section. The broader 3150Å filter samples the SO₂ absorbing region of the Venus spectrum. Conversely, the narrower 3430Å filter samples the continuum region. The interference filter images were flat fielded and the sky background was removed. Three sets of images ratios were obtained, but only one set is presented in Figs. 4a-c, as the other sets showed the same feature morphology. Both of the interference filter images show the classical "Y" feature as shown in surface intensity plots in Fig. 4a, and 4b. The corresponding ratio image of the two filters is basically flat, with only a trace of the "Y" feature visible at the 2% level in the ratio image (Fig.4c). From the lack of major structure in the ratio image we can conclude that the absorber causing the "Y" feature is not SO₂ gas.

MODEL ATMOSPHERE

The model atmosphere used in this analysis is similar to the one used in the analysis of the Pioneer Venus observations (Esposito *et al.* 1979, 1988) and the previous IUE observations (Na *et al.* 1990). In this model, sulfuric acid aerosols with a radius of about 1 μm are mixed uniformly with Rayleigh scattering gases throughout the cloud layer. There are two wavelength-independent absorbers. First, the aerosols are assumed to have a single scattering albedo of 0.98 (Kawahata and Hansen 1975), and second a pure absorbing layer with an optical depth of 0.2 is added at an altitude of 75 mbar. The variable parameters in this model are the mixing ratios of SO_2 at the cloud top (40 mbar level), and the scale height of SO_2 at the same altitude. Model spectra were calculated using a radiative transfer code utilizing the Markov chain method (Esposito and House 1978, Esposito 1979). Each model calculation takes into account the multiple scattering and the vertical inhomogeneity of the atmosphere.

Models used in the analysis of ground based data are list below.

Model name	Mixing ratio	Scale height
E3	100 ppb	3 km
E4	100 ppb	4 km
G3	250 ppb	3 km
G5	250 ppb	5 km
H3	500 ppb	3 km
K3	1000 ppb	3 km

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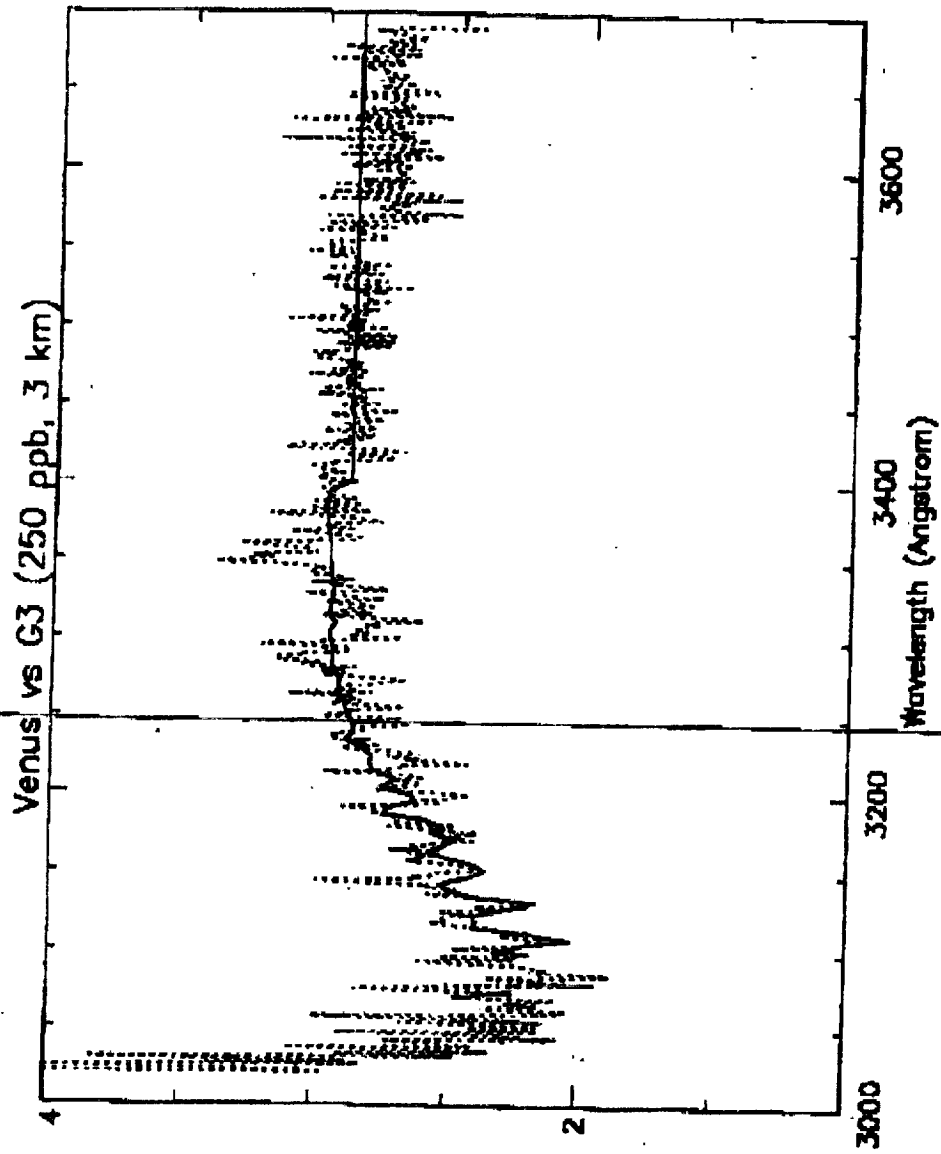
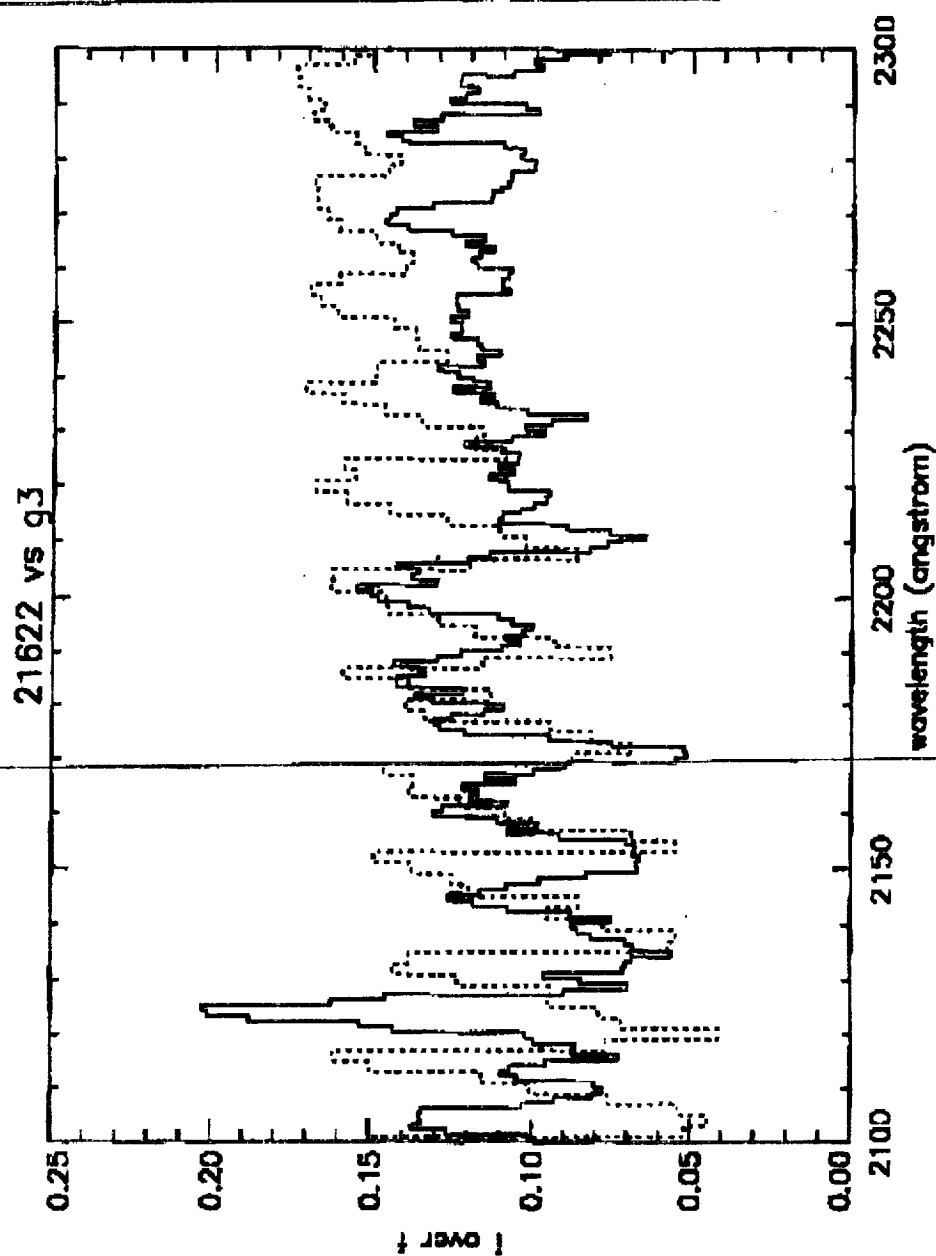


Figure 5: Disk-averaged reflectance spectrum of Venus with best fit SO₂ model.

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Figure 6: IUE short wavelength spectrum with best fit SO₂ model.

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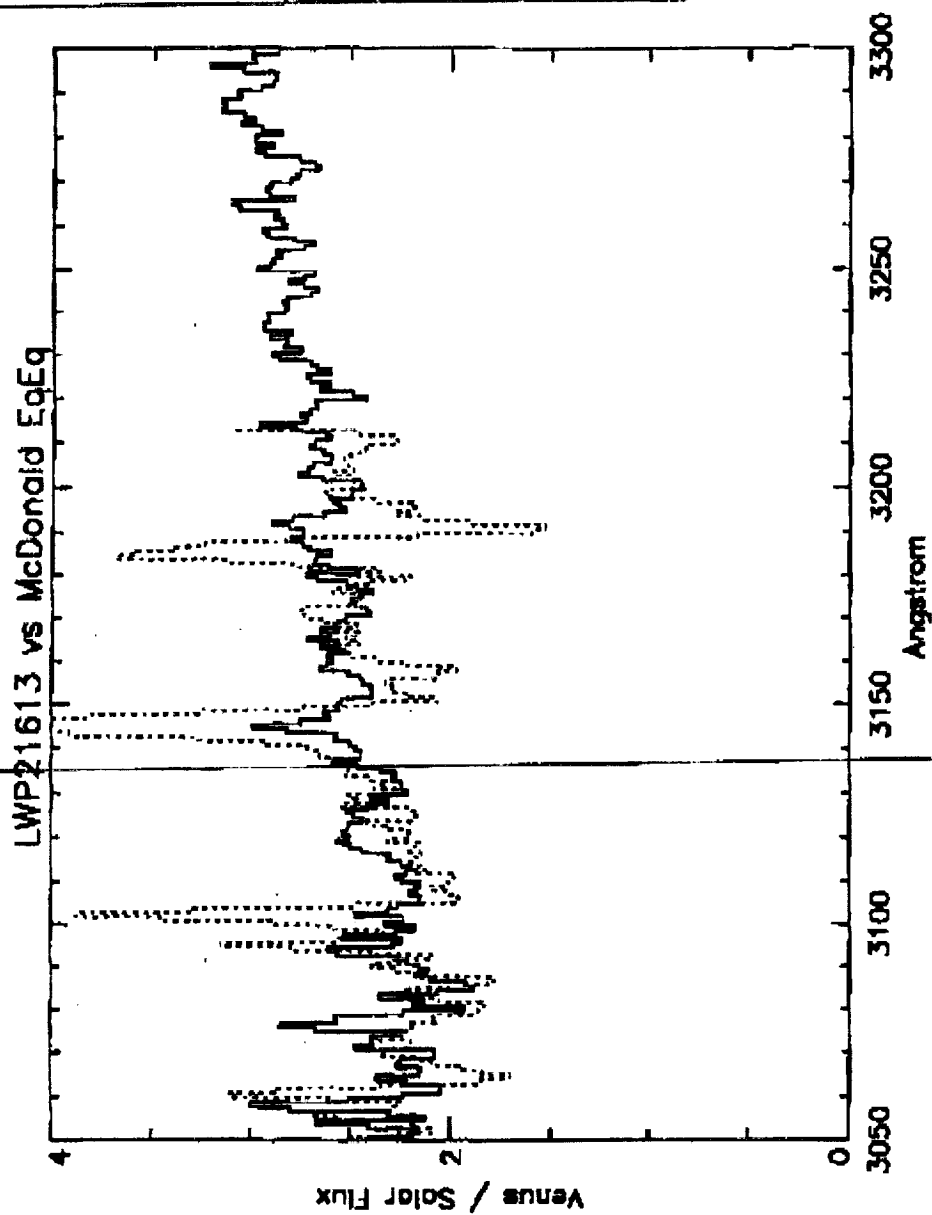


Figure 7: Over plot of IUE long wavelength spectrum and disk-averaged ground-based spectrum.

DISCUSSION

The best fit model to the disk-averaged ground-based spectrum is the G3 model which has an SO₂ abundance of 250 ppb at the 40 mb level (Fig. 5). The low signal and extinction corrections create problems in the ratio spectra below 3050Å. The models with smaller abundances (100 ppb) do not fit the data at all. The IUE spectra are both fit with the G3 model (250 ppb and a scale height of 3 km). The fit to the short wavelength region is shown in Fig. 6. The fits show be considered as preliminary because of the IUE pointing uncertainties which influence the setting of the absolute flux level. Fig. 7 shows the overplot of the long wavelength IUE data with the disk-average ground-based data. There are some discrepancies but the overall match of the slope and the SO₂ band heads is quite good.

Previous IUE spectra and Pioneer Venus spectra have supported a decade-long decline (Na, et al 1990, *JGR* 95, 7485) in the SO₂ abundance since its independent discovery in 1978 by IUE (Conway, et al., 1979, *Geophy Res. Lett.* 6, 629). Pioneer Venus (Stewart, et al 1979, *Science* 203, 777) and ground-based observations (Barker, 1979, *Geophy Res. Lett.* 6, 177). Recently, Na has analyzed all the SO₂ data from IUE, Pioneer Venus, Venera-15 and UV sounding rockets and these data are presented in Fig. 9. When we add the new abundance points for November 1991, it appears that the SO₂ abundance has started to increase during 1991. Until further observations can be made of Venus and the 1991 Pioneer Venus data set can be analyzed, we cannot determine if we have seen an injection event in 1991 or the data are showing a periodic cycle in the SO₂ abundance.

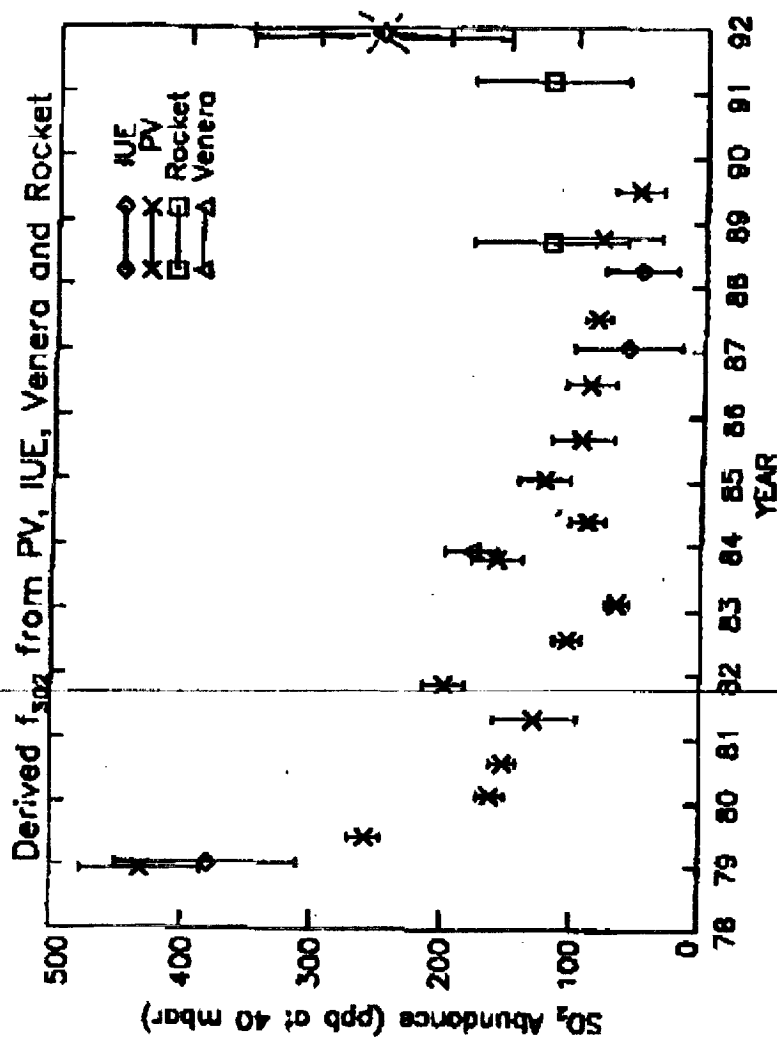


Figure 8: A mixing ratio of SO₂ derived from the IUE, rocket, Pioneer Venus, Venera-15 and ground-based observations.

SUMMARY

- An SO₂ abundance of 250 ppb at 40 mb fits both the IUE and ground-based reflectance spectra.
- Ratio images show that the absorber causing the "Y" feature is not SO₂ gas.
- The long term decline in the SO₂ abundance between 1979 and 1989 has stopped and may be increasing, based on the 1991 measurement made by UV sounding rocket, ground-based and IUE spectra.

FUTURE WORK

- Analyze the 1991 IUE and ground-based data from adjacent days, but the data is of poorer quality.
- Observe Venus with IUE and ground-based techniques in early 1993 to determine, if the SO₂ abundance increase has continued.
- Analyze the available 1991 Pioneer Venus data.